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This project was devoted to the design and computational characterization of several types of real-time autonomous neural network architectures. These architectures were used to explain and predict difficult data bases about brain and behavior, as well as to generate solutions to outstanding technological problems.

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U.S. Army Research Office
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REAL-TIME IMAGE PROCESSING ARCHITECTURES FOR PERCEPTUAL GROUPING, DEPTH SEGREGATION, AND OBJECT RECOGNITION

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April 15, 1985—April 14, 1988

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TABLE OF CONTENTS

PART I

BOOKS AND ARTICLES PARTIALLY SUPPORTED BY THE ARMY RESEARCH OFFICE

APRIL 15, 1985—APRIL 14, 1988

BOOKS

1. Grossberg, S. (Ed.), **The adaptive brain, I: Cognition, learning, reinforcement, and rhythm**. Amsterdam: Elsevier/North-Holland, 1987. (*+)

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PART II

STATEMENT OF THE PROBLEMS STUDIED AND MOST IMPORTANT RESULTS

This project was devoted to the design and computational characterization of several types of real-time autonomous neural network architectures. These architectures were used to explain and predict difficult data bases about brain and behavior, as well as to generate solutions to outstanding technological problems. Projects studied included:

A. Self-Organizing Pattern Recognition and Hypothesis Testing Architectures

Self-organizing adaptive pattern recognition and hypothesis testing architectures were characterized that are capable of learning and recognition in a stable fashion in response to complex, noisy, nonstationary environments; in particular, in response to arbitrary sequences of analog or binary input patterns. This work was carried out jointly by Gail Carpenter and Stephen Grossberg, leading to two new Adaptive Resonance Theory architectures, ART 1 and ART 2, which have received wide attention.

B. Vision Architecture for Emergent Binocular Boundary Fusion and Segmentation

An extension of the monocular Boundary Contour System for emergent boundary segmentation of Grossberg and Mingolla was carried out to include binocular segmentation by Grossberg. This work illustrates how binocular image data about boundaries, textures, and curved surfaces may be cooperatively synthesized into a fused multiple-scale representation of 3-D form. This architecture was used to explain and successfully predict a large data base about visual perception, psychophysics, and neurophysiology, and is being applied to technological problems.

In particular, Grossberg and Marshall have shown how self-similar properties of this multiple-scale network can generate an internal code in which individual nodes of the network, which model complex cells in the mammalian visual cortex, can multiplex information about image position, orientation, spatial frequency, positional disparity, and orientational disparity in a manner that executes the size-disparity correlation found in human psychophysical data.

C. Vision Architecture for Perception of Invariant Surface Color under Variable Illumination Conditions

Grossberg and Todorović have developed a neural network architecture which automatically discounts variable illumination conditions and generates a filled-in representation of surface brightness and color. This model is shown to explain a body of psychophysical and perceptual data that is an order of magnitude larger than previous models could explain.

D. Multiple-Scale Pattern Recognition Architecture for Real-Time Coding of Speech, Language, and Other Time-Series

Cohen and Grossberg have designed a self-similar multiple-scale cooperative-competitive feedback network, called a masking field, that is capable of autonomously encoding the most salient parts of a data stream as it is registered through time in a working memory representation.

Further details of these projects are described in the enclosed summaries taken from the project's semi-annual progress reports.

1985 PROGRESS REPORT

REAL-TIME IMAGE PROCESSING ARCHITECTURES FOR PERCEPTUAL GROUPING, DEPTH SEGREGATION, AND OBJECT RECOGNITION

Contract ARO-DAAG-29-85-K-0095

Principal Investigator: Stephen Grossberg

Institution: Boston University

CURRENT RESEARCH

Carpenter and Grossberg are developing real-time parallel architectures for attentive pattern recognition machines which are capable of self-organizing, self-stabilizing, and self-scaling their learned recognition codes in response to arbitrary lists of arbitrarily many input patterns of variable complexity. They have mathematically proved the key properties of these systems. Grossberg has introduced a real-time parallel architecture for automatic three-dimensional form and color perception, which is capable of handling boundary synthesis, textural segmentation, and smoothly shaded surface interpretation in a unified fashion. Grossberg and Mingolla are refining the competence of the system for segmentation and shape-from-shading using systematic computer simulations. Grossberg and Marshall are showing how a particular stage of the circuit can generate a binocularly deformable space whose individual nodes can multiplex information about spatial frequency, orientation, positional disparity, orientational disparity, and amount of contrast. Todorović has just arrived and is working with Grossberg to design systems capable of extracting invariant color and brightness signals from noisy visual environments.

RECENT ACHIEVEMENTS

These results are based upon (1) an identification of several new uncertainty principles in computational vision, and an analysis of the resolution of informational uncertainty using suitably defined parallel and hierarchical processes; (2) new ideas in dissipative statistical mechanics, nonlinear dynamical systems, and geometry; and (3) new context-sensitive definitions of signal and noise that are appropriate for a self-organizing pattern recognition system. In summary, our recent breakthroughs in computational vision and adaptive pattern recognition have been predicated on new mathematical ideas that are qualitatively different than the nineteenth-century mathematical concepts which are used in many alternative models.

MANUSCRIPTS PUBLISHED OR SUBMITTED FOR PUBLICATION

#*1. Carpenter, G.A. and Grossberg, S., Category learning and adaptive pattern recognition: A neural network model. In **Proceedings of the third Army conference on applied mathematics and computing, 1985**.

*+2. Carpenter, G.A. and Grossberg, S., A massively parallel architecture for a self-organizing neural pattern recognition machine. *Computer Vision, Graphics, and Image Processing*, in press, 1986.

*+3. Cohen, M.A. and Grossberg, S., Adaptive coding of unitized perceptual groupings: Neural association, competition, and modulation. Submitted for publication, 1986.

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* Also supported in part by the Air Force Office of Scientific Research.

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SEMI-ANNUAL PROGRESS REPORT

Contract ARO DAAG-29-85-K-0095
Proposal ARO 22399-MA

REAL-TIME IMAGE PROCESSING ARCHITECTURES FOR PERCEPTUAL GROUPING, DEPTH SEGREGATION, AND OBJECT RECOGNITION

Stephen Grossberg, Principal Investigator
Center for Adaptive Systems
Boston University

January 1, 1986—June 30, 1986

PART I

BOOKS AND ARTICLES PARTIALLY SUPPORTED BY THE ARMY RESEARCH OFFICE

JANUARY 1, 1986—JUNE 30, 1986

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2. Grossberg, S. (Ed.), **The Adaptive Brain, II: Vision, Speech, Language, and Motor Control**. Amsterdam: North-Holland, in press, 1986 (#*+).

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ARTICLES

1. Carpenter, G.A. and Grossberg, S., A massively parallel architecture for a self-organizing neural pattern recognition machine. *Computer Vision, Graphics, and Image Processing*, in press, 1986 (*+).

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PART II

CURRENT RESEARCH

Carpenter and Grossberg have continued their research on developing real-time parallel architectures for attentive pattern recognition machines which are capable of self-organizing, self-stabilizing, and self-scaling their learned recognition codes and directly accessing these codes after learning by disengaging a self-adjusting parallel memory search. They are now analysing how such an Adaptive Resonance Theory (ART) architecture can learn in response to arbitrary sequences of nonnegative patterns. When this ART architecture is in place, it can readily be applied to design a pattern recognition machine capable of learning, without a teacher, to classify objects into codes which are invariant under size, translation, and rotation.

Grossberg has further developed a real-time parallel architecture for automatic preattentive 3-D form and color perception. This architecture combines boundary, texture, shading, and stereo information into a more predictive representation than could any single type of visual information operating alone. Grossberg has just completed a major two-part article on this architecture for *Perception and Psychophysics*, which uses the architecture to analyse a large data base from visual psychophysics, perception, and physiology.

Grossberg and Mingolla have been developing the architecture by doing computer simulations of surface perception, notably shape-from-shading. Their work stimulated Todd and Akerstrom of Brandeis University to test the architecture's predictions on their data about shape-from-texture. The lowest correlation of the Todd-Akerstrom data with test measures derived from the model was .985, which is substantially higher than that of competing theories. Efforts have been begun to analyse how variants of the architecture can be used to understand shape-from-motion.

Cohen and Grossberg have completed an analysis of adaptive coding by a masking field architecture. A masking field architecture is a multiple scale neural network architecture which reacts to input patterns via an adaptive filter by generating a distributed activation code for pattern wholes, salient parts, and predictions. It thereby provides a solution of the credit assignment problem and provides an alternative to the Hough transform. The associative learning law in the adaptive filter is designed to spatially sharpen the distributed code as the input patterns become more familiar. It was also shown that the code becomes spatially sharper as it predicts the input pattern with greater certainty.

Dr. Todorović arrived in January. He is working with Professor Grossberg on designing cooperative-competitive neural networks which react to input patterns by automatically changing their gain to suppress spurious illumination information and thereby extract brightness and color Feature Contour signals. These signals can be used by the Grossberg architecture to generate a representation of 3-D form which is not destroyed by unpredictable changes in illumination. Todorović is also doing computer simulations to generalize the Cohen-Grossberg filling-in model from 1-dimensional to 2-dimensional applications. The design of a network wherein Feature Contour signals input to a filling-in process is being perfected by comparing its performance with that of human psychophysical data on brightness and color perception.

Jon Marshall, a graduate student, is developing computer simulations with Professor Grossberg of a network model wherein spatial patterns of activity over a network F_1, which *as a whole* code properties of position, orientation, spatial frequency, and disparity of contrasts in pairs of image regions, can be multiplexed by *individual* cells at the next processing level F_2. This network models arrays of simple cells (F_1) and complex cells (F_2) in visual cortex (Area 17). Once this model is perfected, the outputs from the network F_2 can be used as inputs to the boundary completion and segmentation network, called the

CC Loop, of Grossberg's 3-D architecture. The function of the CC Loop is to extract and complete a globally consistent binocular segmentation of the visual information found in pairs of monocular images, while suppressing binocularly discordant monocular data.

Professor Grossberg has also written articles on adaptive sensory-motor control and on how limited capacity attentional resources are regulated by environmental feedback in the form of reinforcement (with Professor Daniel Levine of the University of Texas). Both of these projects develop neural networks which were discovered at the Center for Adaptive Systems. The motor control work, in particular, suggests new architectures for adaptive robots capable of self-calibrating their operating parameters in response to unexpected changes in plant characteristics.

Abstracts and Tables of Contents of several articles follow.

A MASSIVELY PARALLEL ARCHITECTURE FOR A SELF-ORGANIZING NEURAL PATTERN RECOGNITION MACHINE

Gail A. Carpenter† and Stephen Grossberg‡

Computer Vision, Graphics, and Image Processing, in press

A neural network architecture for the learning of recognition categories is derived. Real-time network dynamics are completely characterized through mathematical analysis and computer simulations. The architecture self-organizes and self-stabilizes its recognition codes in response to arbitrary orderings of arbitrarily many and arbitrarily complex binary input patterns. Top-down attentional and matching mechanisms are critical in self-stabilizing the code learning process. The architecture embodies a parallel search scheme which updates itself adaptively as the learning process unfolds. After learning self-stabilizes, the search process is automatically disengaged. Thereafter input patterns directly access their recognition codes without any search. Thus recognition time does not grow as a function of code complexity. A novel input pattern can directly access a category if it shares invariant properties with the set of familiar exemplars of that category. These invariant properties emerge in the form of learned critical feature patterns, or prototypes. The architecture possesses a context-sensitive self-scaling property which enables its emergent critical feature patterns to form. They detect and remember statistically predictive configurations of featural elements which are derived from the set of all input patterns that are ever experienced. Four types of attentional process—priming, gain control, vigilance, and intermodal competition—are mechanistically characterized. Top-down priming and gain control are needed for code matching and self-stabilization. Attentional vigilance determines how fine the learned categories will be. If vigilance increases due to an environmental disconfirmation, then the system automatically searches for and learns finer recognition categories. A new nonlinear matching law (the 2/3 Rule) and new nonlinear associative laws (the Weber Law Rule, the Associative Decay Rule, and the Template Learning Rule) are needed to achieve these properties. All the rules describe emergent properties of parallel network interactions. The architecture circumvents the noise, saturation, capacity, orthogonality, and linear predictability constraints that limit the codes which can be stably learned by alternative recognition models.

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CORTICAL DYNAMICS OF THREE-DIMENSIONAL FORM, COLOR, AND BRIGHTNESS PERCEPTION, I: MONOCULAR THEORY

and

CORTICAL DYNAMICS OF THREE-DIMENSIONAL FORM, COLOR, AND BRIGHTNESS PERCEPTION, II: BINOCULAR THEORY

Stephen Grossberg†

Perception and Psychophysics, in press

A real-time visual processing theory is developed of how three-dimensional form, color, and brightness percepts are coherently synthesized. The theory describes how several fundamental uncertainty principles which limit the computation of visual information at individual processing stages are resolved through parallel and hierarchical interactions among several processing stages. The theory hereby provides a unified analysis and many predictions of data about stereopsis, binocular rivalry, hyperacuity, McCollough effect, textural grouping, border distinctness, surface perception, monocular and binocular brightness percepts, filling-in, metacontrast, transparency, figural aftereffects, lateral inhibition within spatial frequency channels, proximity-luminance covariance, tissue contrast, motion segmentation, and illusory figures, as well as about reciprocal interactions among the hypercolumns, blobs, and stripes of cortical areas V1, V2, and V4. Monocular and binocular interactions between a Boundary Contour (BC) System and a Feature Contour (FC) System are developed. The BC System, defined by a hierarchy of oriented interactions, synthesizes an emergent and coherent binocular boundary segmentation from combinations of unoriented and oriented scenic elements. These BC System interactions instantiate a new theory of stereopsis, and of how mechanisms of stereopsis are related to mechanisms of boundary segmentation. Interactions between the BC System and FC System explain why boundary completion and segmentation processes become binocular at an earlier processing stage than color and brightness perception processes. The new stereopsis theory includes a new model of how chromatically broad-band cortical complex cells can be adaptively tuned to multiplex information about position, orientation, spatial frequency, positional disparity, and orientational disparity. These binocular cells input to spatially short-range competitive interactions (within orientations and between positions, followed by between orientations and within positions) which initiate suppression of binocular double images as they complete boundaries at scenic line ends and corners. The competitive interactions interact via both feedforward and feedback pathways with spatially long-range oriented cooperative gating interactions which generate a coherent, multiple-scale 3-D boundary segmentation as they complete the suppression of double image boundaries. The completed BC System boundary segmentation generates output signals, called Filling-In Generators (FIGs) and Filling-In Barriers (FIBs), along parallel pathways to two successive FC System stages: the Monocular Syncytium and the Binocular Syncytium. FIB signals at the Monocular Syncytium suppress monocular color and brightness signals which are binocularly inconsistent and select binocularly consistent, monocular Feature Contour signals as outputs to the Binocular Syncytium. Binocular matching of these Feature Contour signals further suppresses binocularly inconsistent color and brightness signals. Binocular Feature Contour signals which survive these multiple suppressive events interact with FIB signals at the Binocular Syncytium to fill-in a multiple scale representation of form-and-color-in-depth. To achieve these properties distinct syncytia correspond to each spatial scale of the

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BC System. Each syncytium is composed of opponent subsyncytia which generate output signals through a network of double opponent cells. Although composed of unoriented wavelength-sensitive cells, double opponent networks detect oriented properties of form when they interact with FIG signals, yet also generate nonselective properties of binocular rivalry. Electrotonic and chemical transmitter interactions within the syncytia are formally akin to interactions in H1 horizontal cells of turtle retina. The cortical syncytia are hypothesized to be encephalizations of ancestral retinal syncytia. In addition to double opponent cell networks, electrotonic syncytial interactions, and resistive gating signals due to BC System outputs, FC System processes also include habituative transmitters and non-Hebbian adaptive filters that maintain the positional and chromatic selectivity of Feature Contour interactions. Alternative perceptual theories are evaluated in light of these results. The theoretical circuits provide qualitatively new design principles and architectures for computer vision applications.

MASKING FIELDS: A MASSIVELY PARALLEL NEURAL ARCHITECTURE FOR LEARNING, RECOGNIZING, AND PREDICTING MULTIPLE GROUPINGS OF PATTERNED DATA

Michael A. Cohen† and Stephen Grossberg‡

Applied Optics, in press

A massively parallel neural network architecture, called a *masking field*, is characterized through systematic computer simulations. A masking field simultaneously detects multiple groupings within its input patterns and assigns weights to the codes for these groupings which are predictive with respect to the contextual information embedded within the patterns and the prior learning of the system. A masking field automatically rescales its sensitivity as the overall size of an input pattern changes, yet also remains sensitive to the microstructure within each input pattern. In this way, a masking field distinguishes between codes for pattern wholes and for pattern parts, yet amplifies the code for a pattern part when it becomes a pattern whole in a new input context. Such a capability is useful in speech recognition, visual object recognition, and cognitive information processing. A masking field F_2 performs a new type of multiple scale analysis in which unpredictive list codes are competitively masked, or inhibited, and predictive codes are amplified in direct response to trainable signals from an adaptive filter $F_1 \rightarrow F_2$ that is activated by an input source F_1. A masking field exhibits an adaptive sharpening property whereby a familiar input pattern causes a more focal spatial activation of its recognition code than an unfamiliar input pattern. The recognition code also becomes less distributed when an input pattern contains more information on which to base an unambiguous prediction of which input pattern is being processed. Thus a masking field suggests a solution of the credit assignment problem by embodying a real-time code for the predictive evidence contained within its input patterns. An absolutely stable design for a masking field is disclosed through an analysis of the computer simulations. This design suggests how associative mechanisms, multiple-scale competitive interactions, and modulatory gating signals can be joined together to regulate the learning of unitized recognition codes. Data about the neural substrates of learning and memory are compared with these mechanisms.

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NEURAL DYNAMICS OF SURFACE PERCEPTION: BOUNDARY WEBS, ILLUMINANTS, AND SHAPE-FROM-SHADING

Stephen Grossberg† and Ennio Mingolla‡

Computer Vision, Graphics, and Image Processing, in press

A real-time visual processing theory is used to provide a new approach to the analysis of surface perception, notably shape-from-shading. The theory has elsewhere been used to explain data about boundary detection and completion, textural segmentation, depth perception, color and brightness perception, and striate-prestriate cortical interactions. Neural network interactions within a multiple scale Boundary Contour (BC) System and Feature Contour (FC) System are used to explain these phenomena. Each spatial scale of the BC System contains a hierarchy of orientationally tuned interactions, which can be divided into two successive subsystems called the OC Filter and the CC Loop. The OC Filter contains two successive stages of oriented receptive fields which are sensitive to different properties of image contrasts. The OC Filter generates inputs to the CC Loop, which contains successive stages of spatially short-range competitive interactions and spatially long-range cooperative interactions. Feedback between the competitive and cooperative stages synthesizes a coherent, multiple scale structural representation of a smoothly shaded image, called a *boundary web*. Such a boundary web regulates multiple-scale filling-in reactions within the FC System which generate a percept of form-and-color-in-depth. Computer simulations establish key properties of a boundary web representation: nesting of boundary web reactions across spatial scales, coherent completion and regularization of boundary webs across incomplete image data, and relative insensitivity of boundary webs to illumination level and highlights. The theory clarifies data about interactions between brightness and depth percepts, transparency, influences of highlights on perceived surface glossiness, and shape-from-texture gradients. The total network suggests a new approach to the design of computer vision systems, and promises to provide a universal set of rules for 3-D perceptual grouping of scenic edges, textures, and smoothly shaded regions.

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NEURAL DYNAMICS OF ATTENTIONALLY MODULATED PAVLOVIAN CONDITIONING: BLOCKING, INTER-STIMULUS INTERVAL, AND SECONDARY REINFORCEMENT

Stephen Grossberg† and Daniel S. Levine

A neural model of Pavlovian conditioning is developed through computer simulations. The model reproduces properties of blocking, overshadowing, inverted-U in learning as a function of interstimulus interval, anticipatory conditioned responses, secondary reinforcement, attentional focussing by conditioned motivational feedback, and limited capacity short term memory processing. Conditioning occurs from sensory representations to drive representations ("conditioned reinforcer" learning), from drive representations to sensory representations ("incentive motivation" learning), and from sensory representations to motor representations ("habit" learning). The conditionable pathways contain long term memory traces that obey a non-Hebbian associative law. The neural model embodies a solution to two key design problems of Pavlovian conditioning: the synchronization problem and the persistence problem. The results contradict the claim of Sutton and Barto (1981) that an associative theory of the present type cannot explain these data. They also challenge all mammalian conditioning models in which attentional and motivational feedback mechanisms are not explicitly incorporated, and in which a Hebbian synaptic law is used. Invertebrate conditioning models for *Aplysia* and *Hermissenda* are compared with mammalian modelling results. A general prediction about conditioning, called the Secondary Conditioning Alternative, is suggested to hold across all species, both vertebrate and invertebrate.

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COOPERATIVE SELF-ORGANIZATION OF MULTIPLE NEURAL SYSTEMS DURING ADAPTIVE SENSORY-MOTOR CONTROL

Stephen Grossberg†

Aims and Methods in Neuroethology, D.M. Guthrie (Ed.)
Manchester University Press, in press, 1986

TABLE OF CONTENTS

† Supported in part by the Air Force Office of Scientific Research (AFOSR 85-0149 and AFOSR F49620-86-C-0037), the Army Research Office (ARO DAAG-29-85-K-0095), and the National Science Foundation (NSF IST-84-17756).

SEMI-ANNUAL PROGRESS REPORT

Contract ARO DAAG-29-85-K-0095
Proposal ARO 22399-MA

REAL-TIME IMAGE PROCESSING ARCHITECTURES FOR PERCEPTUAL GROUPING, DEPTH SEGREGATION, AND OBJECT RECOGNITION

Stephen Grossberg, Principal Investigator
Center for Adaptive Systems
Boston University

June 30, 1986—December 31, 1986

PART I

PUBLICATIONS PARTIALLY SUPPORTED BY THE U.S. ARMY RESEARCH OFFICE APRIL 15, 1985—DECEMBER 31, 1986

1. Carpenter, G.A., Cohen, M.A., and Grossberg, S., Computing with neural networks: The role of symmetry. *Science*, in press, 1987. (*+)

2. Carpenter, G.A. and Grossberg, S., Category learning and adaptive pattern recognition: A neural network model. In **Proceedings of the Third Army Conference on Applied Mathematics and Computing, 1985**. (#*)

3. Carpenter, G.A. and Grossberg, S., A massively parallel architecture for a self-organizing neural pattern recognition machine. *Computer Vision, Graphics, and Image Processing*, 1987, **37**, 54–115. (*+)

4. Carpenter, G.A. and Grossberg, S., Adaptive resonance theory: Stable self-organization of neural recognition codes in response to arbitrary lists of input patterns. *Proceedings of the Cognitive Science Society*, 1986. (*+)

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15. Grossberg, S. and Marshall, J., A computational model of how cortical complex cells multiplex information about position, contrast, orientation, spatial frequency, and disparity. In preparation. (*)

16. Grossberg, S. and Mingolla, E., Nonlinear neural dynamics of visual segmentation. In **Proceedings of the Third Army Conference on Applied Mathematics and Computing, 1985**. (*)

17. Grossberg, S. and Mingolla, E., Neural dynamics of perceptual grouping: Textures, boundaries, and emergent segmentations. *Perception and Psychophysics*, 1985, **38**, 141–171. (*)

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19. Grossberg, S. and Mingolla, E., The role of illusory contours in visual segmentation. In G. Meyer and S. Petry (Eds.), **Proceedings of the International Conference on Illusory Contours**. Pergamon Press, 1987. (*+)

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21. Grossberg, S. and Schmajuk, N.A., Neural dynamics of attentionally-modulated Pavlovian conditioning: Conditioned reinforcement, inhibition, and opponent processing. Submitted for publication, 1987. (*+)

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23. Todorović, D., Hemispheric differences in case processing. Submitted for publication, 1987.

24. Todorović, D., The Craik-O'Brien-Cornsweet effect: New varieties and their theoretical implications. Submitted for publication, 1987.

* Also supported in part by the Air Force Office of Scientific Research.

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PART II

CURRENT RESEARCH

Carpenter and Grossberg have completed a conceptual and computer simulation analysis of how time series of *analog* input patterns can be automatically categorized by a real-time Adaptive Resonance Theory (ART) architecture, called ART 2. Such an architecture is a parallel neural network design for an attentive pattern recognition machine which is capable of self-organizing, self-stabilizing, and self-scaling its learned recognition codes and directly accessing these codes after learning occurs by disengaging an efficient self-adjusting parallel search that helps to discover a globally self-consistent recognition code during the learning phase. These computer simulations are being written up in an invited article to *Applied Optics*.

Carpenter and Grossberg have also been successfully testing ART 2 on image-based noisy data sent to us by the M.I.T. Lincoln Laboratory.

Grossberg and Todorović have completed their development and analysis of a neural network architecture to explain a large psychophysical data base on brightness perception. These data clarify how humans can discount the effects of variable illumination to generate a representation of a scene's 3-D form which is not distorted by unpredictable changes in illumination. The model was developed through systematic computer simulations which have led to a unified explanation of a perceptual data base that is much larger than that explained by alternative theories. This explanatory range has been achieved through the discovery of qualitatively new principles and mechanisms for the design of an automatic vision machine.

Grossberg has begun to analyse mechanisms for the automatic segmentation of form-from-motion information.

Grossberg and Schmajuk have completed an article showing how attention can be quickly focussed upon sensory information which has led to successful predictive performance in the past. Successful prediction is here defined by feedback from reinforcements that are contingent upon the performance. Otherwise expressed, these results clarify how to design the adaptive nonlinear feedback control of an image processing machine capable of flexibly allocating its resources to the processing of sensory information which promises to satisfy the machine's internal criteria of success.

Grossberg has noted that the Cohen-Grossberg masking field equations for predictively encoding an input pattern's most salient groupings can be rewritten as a special case of the Cohen-Grossberg design for a content addressable memory (CAM) machine. This change of variables clarifies why the masking field can store a stable CAM in response to arbitrary input patterns. Grossberg also showed that the Cohen-Grossberg design includes essentially all other known continuous time neural network CAM equations in the literature. These include the Brain-State-in-a-Box model, the Boltzmann machine, the additive model, the shunting model, and the McCulloch-Pitts model.

Grossberg and Marshall are carrying out computer simulations to show how to design an adaptive filter that multiplexes scenic information about position, orientation, spatial frequency, and binocular disparity.

SEMI-ANNUAL PROGRESS REPORT

Contract ARO DAAG-29-85-K-0095
Proposal ARO 22399-MA

REAL-TIME IMAGE PROCESSING ARCHITECTURES FOR PERCEPTUAL GROUPING, DEPTH SEGREGATION, AND OBJECT RECOGNITION

Stephen Grossberg, Principal Investigator
Center for Adaptive Systems
Boston University

January 1, 1987—June 30, 1987

PART I

BOOKS AND ARTICLES PARTIALLY SUPPORTED BY THE ARMY RESEARCH OFFICE

APRIL 15, 1985—JUNE 30, 1987

BOOKS

1. Grossberg, S. (Ed.), **The adaptive brain, I: Cognition, learning, reinforcement, and rhythm**. Amsterdam: Elsevier/North-Holland, 1987. (*+)

2. Grossberg, S. (Ed.), **The adaptive brain, II: Vision, speech, language, and motor control**. Amsterdam: Elsevier/North-Holland, 1987. (*+)

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1. Carpenter, G.A., Cohen, M.A., and Grossberg, S., Computing with neural networks: The role of symmetry. *Science*, 1987, **235**, 1226–1227. (*+)

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vision: Multiple scale segmentation and regularization. *Proceedings of the First International Conference on Neural Networks*, San Diego, IEEE, 1987. (*)

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PART II
CURRENT RESEARCH

Carpenter and Grossberg have completed an invited article for *Applied Optics* concerning how time series of analog input patterns can be automatically learned and recognized by a real-time Adaptive Resonance Theory (ART) architecture, called ART 2 (see previous progress report).

Carpenter and Grossberg have also reported results on using ART 2 to perform *invariant* self-organizing pattern recognition tasks using a front-end that exploits laser radar sensors, a Boundary Contour segmentation network, and a Fourier-Mellon filter. This presentation will appear as part of the proceedings of the IEEE First International Conference on Neural Networks (ICNN).

Grossberg and Todorović have modified and expanded their article on brightness perception in response to positive referee reports from *Perception and Psychophysics* (see previous summary). The article is now in press.

Grossberg and Schmajuk have modified and expanded their article on the opponent processing mechanisms whereby reinforcement focuses attention upon events which have led to successful predictive performance in the past (see previous report). This article is now in press in *Psychobiology*.

Grossberg and Marshall have written up and reported at the IEEE ICNN meeting their computer simulations to show how to design an adaptive filter that multiplexes scenic information about position, orientation, spatial frequency, and binocular disparity.

Grossberg and Mingolla have written up and reported at the IEEE ICNN meeting computer simulation results concerning how the Boundary Contour System can regularize and complete sharp image boundaries from noisy image data in a self-scaling fashion. Their demonstration of how noise can be annihilated and sharp boundaries coherently generated through noisy image regions suggests a new approach to penetrating camouflage.

Grossberg and Levine have written up and reported their computer simulation results concerning how humans and animals attentionally block events which are accidentally correlated with predictively important consequencs. The results will appear in *Applied Optics*.

Grossberg has written a major integrative article concerning recent results on content-addressable memory, adaptive resonance architectures, and circuits for the self-organization of various invariant properties during real-time pattern recognition and robotics. This article will appear in *Neural Networks*. the official journal of the new International Neural Network Society, of which Grossberg has been elected the first president.

SEMI-ANNUAL PROGRESS REPORT

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PART I
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PART II

CURRENT RESEARCH

Carpenter and Grossberg have worked with Courosh Mehanian at MIT Lincoln Laboratory to begin large-scale computer simulations of the ART 2 self-organizing pattern recognition architecture on a CRAY supercomputer. These simulations will be done to further develop and test their architecture for *invariant* self-organizing pattern recognition in which ART 2 is used as the pattern classifier after the scenic data are preprocessed by a specialized filter that uses laser radar, boundary segmentation, and Fourier-Mellin techniques.

Grossberg has been training Michael Rudd, who came from UC Irvine to replace Dejan Todorović when he left the Center to assume a tenured faculty position. Dr. Rudd was first trained to carry on studies of featural filling-in for analyses of brightness and color perception in which variable illumination conditions are automatically discounted. He is now working with Professor Grossberg on a project to model how rapidly flickering patterned visual stimuli alter the color and form perception of human observers.

Grossberg and Schmajuk have modelled another aspect of how humans and animals process temporally changing stimuli. In particular, they have modelled how humans and animals learn to discriminate the delays between predictive stimuli and their consequencs (e.g., rewards or punishments) and to focus their attention during these learned delays upon the environmental events that predict the consequences. Such vigilance behavior helps to optimize performance when the expected consequence occurs.

Grossberg and Marshall have further modelled, and are now writing up for publication, their work on designing an adaptive filter that multiplexes scenic information about position, orientation, spatial frequency, and binocular disparity before the multiplexed data activate a Boundary Contour System capable of selecting and completing a 3-D segmentation of the globally consistent, and in particular stereoscopically consistent, scenic data.

Grossberg and Mingolla have made progress in designing a Boundary Contour System capable of selecting and completing a globally consistent segmentation of locally ambiguous motion data.

Grossberg has completed the research monograph **Neural Networks and Natural Intelligence** to be published by the MIT Press.

PART IV

PARTICIPATING SCIENTIFIC PERSONNEL

Professor Gail A. Carpenter

Professor Stephen Grossberg

Mr. Jonathan Marshall (received Ph.D. in computer science during the contract period)

Dr. Dejan Todorović (January 1, 1986—October 1, 1987)

Dr. Michael Rudd (July 15, 1987—April 14, 1988)